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Comparative assessment of future power generation technologies based on carbon price development

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A B S T R A C T

The long-term assessment of new electricity generation was performed for various long-run policy scenarios taking into account two main criteria: private costs and external GHG emission costs. Such policy oriented power generation technologies assessment based on carbon price and private costs of technologies can provide information on the most attractive future electricity generation technologies taking into account climate change mitigation targets and GHG emission reduction commitments for world regions.

Analysis of life cycle GHG emissions and private costs of the main future electricity generation technologies performed in this paper indicated that biomass technologies except large scale straw combustion technologies followed by nuclear have the lowest life cycle GHG emission. Biomass IGCC with CO_2 capture has even negative life cycle GHG emissions. The cheapest future electricity generation technologies in terms of private costs in long-term perspective are: nuclear and hard coal technologies followed by large scale biomass combustion and biomass CHPs. The most expensive technologies in terms of private costs are: oil and natural gas technologies. As the electricity generation technologies having the lowest life cycle GHG emissions are not the cheapest one in terms of private costs the ranking of technologies in terms of competitiveness highly depend on the carbon price implied by various policy scenarios integrating specific GHG emission reduction commitments taken by countries and climate change mitigation targets.

Contents

1. Introduction

Efforts towards a sustainable energy system are progressively becoming an issue of paramount importance for decision makers. Efficient production, distribution and use of energy resources and

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provision of equitable and affordable access to energy while ensuring security of energy supply and environmental sustainability are the main energy policy objectives towards a sustainable energy system. Implementation of new energy technologies is a key mean towards a sustainable energy system. Technological advances are of critical importance for the improvement of living conditions, the production and the transportation of the energy and the efficiency of its use thus it is expected to produce major public benefits. New energy technologies can be considered to be an important bridge between the Lisbon strategy objective of making the European Union "the most competitive and dynamic knowledge-based economy in the world" and the EU sustainable development strategy agreed at the Goteborg European Council. Therefore decision makers have to decide from an increasingly diverse mix of new energy technologies, the ones which warrant support, including funding (e.g., R&D support) and other incentives for private sector efforts. However, the identification of these technologies that can comply with the emerging needs and opportunities in the three sustainable development dimensions, namely the economic, environmental and social is a very complex process. The methods and tools are needed to assist policy design, in terms of establishing technological priorities towards a sustainable energy system. The multi-criteria methods can be an important supportive tool in decision making, providing the flexibility and capacity to assess the technologies' implications to the economy, the environment and the social framework. Especially, this is true taking into consideration that many of the key attributes of energy technologies, which are not market-valued and concern the social and environmental dimension of sustainable development, are often excluded from the analysis.

The future development and deployment of new energy technologies highly depend on energy and environmental policies taking into account sustainable development principles and their established binding targets for GHG and other pollutants emissions, renewable energy sources, energy efficiency improvements, etc.

The assessment of innovative energy technologies can be performed based on the economic, environmental and social criteria by applying quantitative and qualitative indicators. Therefore assessment of new energy technologies through a number of criteria is a complex and time consuming task, since the analysis has to face a series of uncertainties such as fossil fuel price, environmental regulations, market structure, technological, and demand and supply uncertainty. Furthermore, sustainability is an inherently vague and complex concept and the implications of sustainable development as a policy objective is difficult to be defined or measured. In particular, the information needed for the evaluation of technologies in terms of their sustainability may be unquantifiable due to its nature or even unavailable. Therefore, appraising energy technologies in terms of their sustainability and competiveness is a really complex task, considering the series of uncertainties and implications that have to be encountered so as to obtain realistic and transparent results.

As climate change mitigation is the central environmental policy in EU and all over the world the long-term assessment of new power technologies based on various long-run policy scenarios is useful for policy makers taking into account just two main criteria: private costs (ALLGC) and external GHG emission costs.

The aim of the paper is to assess the main relevant future electricity generation technologies by integrating price of carbon obtained by policy scenarios run using various energy models in calculating GHG emission externalities for the main future electricity generation technologies.

2. Comparative assessment of energy technologies

2.1. Integrated assessment tools

Integrated assessment consists of the wide-array of tools for managing complex issues [1]. Multi-criteria analysis (MCA) is used for assessments in situations when there are competing evaluation criteria. MCA identifies, in general, goals or objectives and then seeks to spot the trade-offs between them; the ultimate goal is to identify the optimal policy. This approach has the advantage of incorporating both qualitative and quantitative data into the process [2]. The alternative to MCA is cost benefit analysis (CBA). CBA is an applied welfare economics tool with roots reaching back to the early 20th century. It is used for evaluating public or private investment proposals by weighing the costs of the project against the expected benefits. In the realm of sustainability assessment, CBA can be an effective tool for weighing the social costs and benefits of different alternatives in connection with e.g. energy and transports. Efforts have been made through combining two or more different tools to extend the focus of analysis [3]. Examples of this tendency are the simultaneous analysis of a product or service function using life cycle assessment (environmental impact tool), life cycle costing (LCC) (economic tool) and/or the social life cycle assessment. A shortcoming of such an approach is that the overall results of the study are not presently integrated in any manner.

For sustainability assessment of energy technologies integrated tools need to be applied. The combination of indicators framework, LCA, LCC, MCA and integrated indicators approach might be useful for energy technologies assessment including application of conceptual modelling tools and uncertainties analysis therefore in Planets project for probabilistic long-term assessment of new energy technologies scenarios the assessment framework was developed based on these tools.

2.2. Recent approaches used for energy technologies assessment

Within the framework of NEEDS project technology foresight methodology was developed aiming to analyse expected energy technology futures. A large number and EU have established technology foresight projects and emphasised the need of a stronger future orientation in policy development and strategic planning. The technology foresight projects become increasingly usual as an instrument in public governance of research, innovation and technology development.

Technology road mapping is a forward-looking approach developed and widely used to support strategic long-term planning within organizations like industrial companies. Roadmap studies analyse and discuss the road ahead for the development of a specific industrial product or a specific technology. Roadmaps seek to capture the surrounding landscape, threats and opportunities for a particular group of stakeholders in a technology area or in an area of technology application. The technology road mapping approach is increasingly applied in foresight studies, especially in those exercises that are focused upon particular industrial sector like energy sector. It is characteristic of traditional technology road mapping that it describes a specific, partial perspective of energy technologies development with a clearly defined goal. This approach can lead to a comprehensive and multi-facetted understanding of a desirable development path for a technology and of the interplay between different kinds of activities (market, scientific or industrial activities), different drivers of change, etc. In EU NEEDS project [4] technology foresight and LCA approaches were combined for technology assessment. The developed methodological framework comprises three main steps: technology scanning or information gathering; analysis and discussion of the future technology or visioning and synthesis by developing

energy technology road map and description of results or LCA scanning.

Strategic technology roadmap is navigation tool for strategic planning and implementation of research and development investments. European strategic energy plan [5] presents a vision of EU energy future based on efficiency, diversification, decarbonisation and liberalisation and identifies those energy technologies for which it is essential that EU finds more powerful way of mobilising resources in ambitious result-oriented actions to accelerate their pathway to the market. This was achieved by assessing the potential of a set of technologies and barriers and needs for their further development and deployment, highlighting the role of energy technology innovation in support of achieving the EU energy policy goals.

The assessing the value of new energy technologies performed by Stanford University (2002–2007) in the framework Global Climate and Energy Project (GCEP) [6] is based on assessment of the impacts of new energy technologies dependent on the assessments of both their likely costs and performance characteristics including carbon emissions and other environmental impacts, and their likely market penetration under a wide range of possible energy futures.

2.3. Criteria applied for sustainability assessment of energy technologies

There are many examples of energy technologies assessment. Based on the results of survey of energy technologies assessment found in the recent literature and results of EU funded projects, a methodological framework based on indicators set for energy technologies assessment was reviewed in the paper.

In an interagency effort led by the IAEA in cooperation with UNDESA, IEA, the Statistical Office of the European Communities (Eurostat) and the European Environment Agency (EEA) a core set of energy indicators for sustainable development (EISD) has been established [7,9]. By mutual consent, the original set of 41 indicators was reduced to a final core set of 30 indicators. Although the original framework used the DSR approach, it has been modified to follow the recently adopted theme and subtheme framework of UN CSD. The 30 energy indicators for sustainable development presented here are classified according to the three major dimensions of sustainability: economic (16 indicators), environmental (10 indicators) and social (4 indicators).

There were few projects on energy technologies assessment performed in EU applying sustainable energy indicators approach and using various sets of sustainable indicators ranging from quantitative to qualitative. In EUSUSTEL project [8,10] the assessment of energy technologies was based on total social costs as useful indicator to account for overall resource consumption. Private cost of electricity was calculated based on average lifetime levelised generation costs. External costs of electricity generation due to emissions of CO_2, NOx, NMVOC, CH_4, PM_{10}, N_2O and C_{14} have been taken into account [8,10].

Quantitative indicator system that allows assessing the level of sustainability in energy policy, energy supply and use was developed in Switzerland, the Swiss Federal Office of Energy [11]. The defined indicator framework distinguished four types of indicators: impact indicators: impacts of the energy sector on environment, economy and society; activity indicators: description of production and consumption of goods and services in the four consumer groups industry, services trade, households and transport, energy efficiency indicators: they refer to the technical-energetic efficiency of energy extraction, conversion and use and policy indicators: they represent the reactions, which are implemented by energy policy to achieve a more sustainable energy sector. Based on 27 criteria a total of 60 indicators were defined however this indicator sets fits more to sustainability assessment of energy sector as a whole and cannot be applied for technologies assessment within specific energy sectors such as electricity, buildings, etc.

The following conclusions can be drawn from the criteria and indicator survey performed based on the recent literature review. The indicators frameworks applied for sustainability assessment of energy technologies have different scope and focus: sustainable development in general, sustainable development within the energy sector, and sustainable development within specific energy sources. There are wide differences in allocating specific indicators for specific dimensions of sustainable development. There are just few world-wide recognized and well-developed indicators for sustainability assessment of energy technologies applied in all studies. These indicators are mainly applied to electricity and heat sector and are supported by well-developed comprehensive databases. These indicators are: private costs of electricity generation, life cycle external health costs, life cycle environmental external costs, life cycle radionuclides external costs and life cycle emissions of GHG gases.

Summarizing, there are no well-established comprehensive indicators sets supported by databases for sustainability assessment of energy technologies in transport, buildings and industry sectors. The sets of indicators originating from international organizations are not suitable for comparing the sustainability attributes of the major energy sources, in regard to appropriate differentiation between technologies. Most of the indicators sets are primarily based on directly available, simplistic indicators, and there are major consistency problems. Little effort has been made towards aggregation of indicators to support decisions. Earlier studies have not provided a harmonized, recognized set of technology-specific, application-specific numerical indicators. A broad knowledge base is a prerequisite for the establishment of such indicators, and the analytical framework employed in the present study can serve as a basis for this. The indicators set selected for electricity generation technologies sustainability assessment in GaBE study performed by PSI is the most comprehensive one from analysed frameworks and studies [11]. This framework together with some indicators from EU NEEDS [4] and CASES projects [12,13] can serve as the background for technologies assessment.

Climate change is the dominating environmental concern of the international environmental political discussion of today. Global warming is not only an issue for the environment, but rather for human society as a whole, since rising global temperatures might have serious consequences not only on the environment, but on our economy and social life as well. Life cycle GHG emissions indicator reflects the potential negative impacts of the global climate change caused by emissions of greenhouse gases for the production of 1 kWh of electricity. It follows the methodology of IPCC and covers complete energy chains. This indicator was used in almost all studies on energy technologies assessment survived.

Further seeking to integrate long-term technology assessment with results of long-term policy scenarios run in assessing the main relevant power technologies the carbon price obtained by various policy scenarios runs will be used in the calculation of the GHG emission externalities of selected energy technologies.

3. Carbon price development

Within EU FM 7 project Planets [14] aiming at assessment of future energy technologies the assessment of energy technologies was performed based on carbon price development. Seeking to assess energy technologies based on future energy and climate change mitigation policies the information on carbon price developments is crucial in terms of technologies ranking. The

Table 1
GHG reduction commitments applied in policy scenarios.

Regions	Starting date of commitments	Commitments SC1 in 2050 w.r.t. 2005	Commitments SC2 in 2050 w.r.t. 2005
OECD	2015	−80%	−90%
Energy exporting (EEX)	2025	−50%	0%
Developing Asia (Dev. Asia)	2025	+25%	0%
Rest of the world (ROW)	2025	+55%	+100%
World w.r.t. 2005		−28%	−26%

policy scenarios integrating various GHG emission reduction commitments and climate change mitigation targets can provide information on carbon price developments over time frame. The policy oriented assessment of the main selected power generation technologies in this paper will be provided for 2020 and 2050 and for the various regions (World, OECD, Energy Exporting EEX – Russia and mid-East, Developing Asia, DevAsia, Rest of the World, ROW) covered by models (ETSAP-TIAM, DEMETER, GEMINI and WITCH) [15].

The results of various model runs for various policy oriented scenarios will serve as input for energy technologies assessment. 10 policy scenarios runs were performed for 4 models:

- First best scenarios: FB-3p2 and FB-3p5 setting alternative targets after 2050: 3.2 W/m^2 and 3.5 W/m^2.
- Second best policy scenarios:
  1. SC1-3p2 – To reach commitments indicated in Table 1 for SC1 linearly declining from business as usual from start date (Table 1) to the indicated of 2005 emissions. The target after 2050: 3.2 W/m^2
  2. SC1-3p5 – To reach commitments indicated in Table 1 for SC1 linearly declining from business as usual from start date (Table 1) to the indicated of 2005 emissions. The target after 2050: 3.5 W/m^2
  3. SC2-3p2 – To reach commitments indicated in Table 1 for SC2 linearly declining from business as usual from start date (Table 1) to the indicated of 2005 emissions. The target after 2050: 3.2 W/m^2
  4. SC2-3p5 – To reach commitments indicated in Table 1 for SC2 linearly declining from business as usual from start date (Table 1) to the indicated of 2005 emissions. The target after 2050: 3.5 W/m^2.

The set of four variant second best policy scenarios are the same as for four second best scenarios, but with a limitation on the purchasing of carbon permits between 2020 and 2050, during which period at least 80% of abatement (defined as business usual minus the allocation) has been undertaken domestically by each region, and at most 20% of the abatement can be done with international offsets (purchase of permits). The trade restriction is levied from 2050 onwards.

The main indicators or criteria for energy technologies assessment according various policy scenarios will be private costs of energy generation and external costs of GHG emissions integrating carbon price.

The following energy technologies were selected for assessment in power and heat generation sector: hard coal, natural gas, oil, nuclear and biomass. In power sector just base load technologies were assessed. In the following sections of paper based on recent scientific literature review and results of various EU funded projects the range of life cycle GHG emissions and private costs for the selected electricity generation technologies will be derived. The average values of life cycle GHG emissions and private costs were further used for electricity generation technologies policy oriented assessment and ranking. The most competitive energy technologies will be identified based on external costs of GHG emissions and total costs for the main policy scenarios. Policy oriented energy technologies assessment can provide information on the most attractive future energy technologies taking into account climate change mitigation targets and GHG emission reduction commitments for world regions.

Carbon price developments obtained by 10 policy scenario runs for ETSAP-TIAM, DEMETER, GEMINI and WITCH models are presented in Table 2.

Further the policy oriented power and transport technologies assessment will be performed for various policy scenarios (10 scenarios) for 2020 and 2050 time frame and for various regions by calculating external costs of GHG emission using data on carbon price development over time and space obtained by various models (Table 2). Energy technologies in policy oriented assessment will be ranked for various scenarios based on external costs of GHG emissions and also based on the total costs (the sum of external costs of GHG emissions calculated by using carbon price data obtained by various models and private costs).

4. Life cycle GHG emissions and private costs of future electricity generation technologies

4.1. Life cycle GHG emissions of electricity generation technologies

The data on life cycle GHG emissions for specific fuel cycles are necessary seeking to assess external costs of GHG emissions for different energy technologies using information about CO_2 prices over the time and space delivered by various models by running policy scenarios. Life cycle CO_2 emissions from power sector depend strongly upon details of supply chain, production techniques, forestry and agriculture practices, transport distance, etc. Life cycle emissions of GHG emissions in kg (CO_2 eq.)/kWh are selected to assess electricity generation technologies according EU

Table 2
GHG price in 2020 and 2050 EUR (2005)/metric tonne of CO_2 eq.

Fuel or energy type	2020					2050				
	Global	OECD	EEX	DEV Asia	ROW	Global	OECD	EEX	DEV Asia	ROW
REF	0	0	0	0	0	0	0	0	0	0
FB-3p2 scenario	21–89	21–48	21–48	21–48	21–48	176–573	195–573	195–573	195–573	195–573
FB-3p5 scenario	13–52	13–48	13–48	13–48	13–48	89–297	195–297	195–297	195–297	195–297
SC1-3p2 scenario	3–21	3–21	3–21	3–21	3–21	107–248	107–248	107–248	107–248	3–107
SC1-3p5 scenario	3–44	3–13	3–13	3–13	3–13	110–289	110–289	110–289	110–289	110–289
SC2-3p2 scenario	3–14	3–14	3–14	3–14	3–14	110–229	110–229	110–229	110–229	110–229
SC2-3p5 scenario	3–13	3–13	3–13	3–13	3–13	110–268	110–268	110–268	110–268	110–268
VAR1-3p2scenario	0–14	0–14	0–17	0–12	0–12	111–192	113–192	125–192	103–192	103–192
VAR1-3p5 scenario	3–13	3–14	3–15	3–11	3–11	110–238	114–238	120–238	103–238	103–238
VAR2-3p2 scenario	0–13	0–15	0–12	0–12	0–12	105–164	115–164	101–164	101–164	101–164
VAR2-3p5 scenario	3–11	3–15	3–10	3–10	3–10	105–203	114–203	101–203	101–203	101–203

environmental policy priority—climate change mitigation. Climate change is the dominating environmental concern of the international environmental political discussion of today. Global warming is not only an issue for the environment, but rather for human society as a whole, since rising global temperatures might have serious consequences not only on the environment, but on our economy and social life as well. Among the potential consequences are more frequent extreme weather events like heat waves, storms, flooding and droughts, stress due to higher temperatures for plants and humans, rising sea level, and altering occurrence of pathogenic organisms. The indicator reflects the potential negative impacts of the global climate change caused by emissions of greenhouse gases for the production of 1 kWh of electricity.

The principle factors determining the GHG emissions from a fossil fuel power plant is the type of technology (and hence choice of fuel) and its thermal efficiency. In addition, thermal efficiency increases with the load factor (although efficiency reductions can be observed towards achieving full load operation) and therefore GHG emissions from a particular fossil fuel technology will depend on the mode of its operation (e.g. peak load management, base load supply, combined heat and power supply, etc.). The ranges of life cycle GHG emissions for power and heat generation technologies are presented in Table 3. Life cycle GHG emission ranges (from minimal to maximal values) were presented based information provided by various sources [16–19]. The range of direct CO_2 emissions from combustion and total life cycle GHG emissions per technology were calculated in kg/MWh. Further these data will be used for external costs calculation of power generation technologies using carbon price data (EUR/tCO_2) produced by various models for various policy scenarios, regions and time frames.

As one can see from information provided in Table 3 biomass wood chips gasification technologies have the lowest life cycle GHG emissions followed by wood chips CHP large scale. Hard coal technologies have the highest life cycle GHG emissions followed by oil and natural gas technologies. Hard coal IGCC with CO_2 capture technologies has quite low life cycle GHG emission comparable even with large scale wood chips gasification technologies. Nuclear technologies have lower life cycle GHG emission than some biomass technologies for example large scale straw combustion technologies and large scale wood chips combustion technologies. Biomass technologies with CO_2 capture have negative life cycle GHG emissions. Especially high negative GHG emissions are during combustion processes of biomass IGCC with CO_2 capture.

4.2. Private costs of electricity generation

The private costs in EURcnt/kWh are based on the average levelised generating costs (ALLGC) methodology. The methodology calculates the generation costs (in EuroCents/kWh) on the basis of net power supplied to the station busbar, where electricity is fed to the grid. This cost estimation methodology discounts the time series of expenditures to their present values in 2005, which is the specified base year, by applying a discount rate. According to the methodology used in the IEA study in 2005, the levelised lifetime cost per GWh of electricity generated is the ratio of total lifetime expenses versus total expected outputs, expressed in terms of present value equivalent. The total lifetime expenses include the value of the capital, fuel expenses and operation and maintenance expenses, inclusive the rate of return equal to discount rate. The formula to calculate ALLGC is:

$$\mathrm{ALLGC} = \frac{\sum_{t=0}^{T} [I_t + M_t + F_t]/(1+r)^t}{\sum_{t=0}^{T} [E_t]/(1+r)^t} \tag{1}$$

where I_t is the investment expenditures in year t; M_t is the operation and maintenance expenditure in year t; F_t is the fuel expenditures in year t; E_t is the electricity generation in year t and r is the discount rate.

The capital (investment) expenditures in each year include construction, refurbishment and decommissioning expenses. As suggested by OECD the methodology used defines the specific overnight construction cost in €/kW and the expense schedule from the construction period. The overnight construction cost is defined as the total of all costs incurred for building the plant immediately. The operating and maintenance costs (O&M) contribute by a small but no negligible fraction to the total cost. Fixed O&M costs include costs of the operational staff, insurances, taxes, etc. Variable O&M costs include cost for maintenance, contracted personnel, consumed material and cost for disposal of normal operational waste (excluding radioactive waste).

The range of current and long-term private costs (ALLGC) for the same power generating technologies was selected from various information sources [4,8,10,12,18]. In Table 4 the range of current private costs of the selected power generation technologies is presented.

As one see from information provided in Table 4 the cheapest technologies in long-term perspective are: nuclear and hard coal technologies followed by large scale biomass combustion and biomass CHPs. The most expensive technologies in terms of private costs are: oil and natural gas technologies. Therefore the energy technologies having the lowest life cycle GHG emissions are not the most expensive but not the cheapest one in terms of private costs. Therefore the ranking of technologies in terms of competitiveness would highly depend on the carbon price implied by various policy scenarios integrating specific GHG emission reduction commitments taken by countries and set climate change mitigation targets.

Table 3
Life cycle GHG emissions of the main energy technologies in power sector.

Fuel or energy type	Direct CO_2 emissions from combustion		Life cycle CO_2 emissions		Average value, of life cycle GHG emissions (kg/MWh)
	kg/GJ	kg/MWh	kg/GJ	kg/MWh	
Nuclear	2.5 to 30.3	9 to 110	2.8 to 35.9	10 to 130	65
Oil	126.9 to 300.7	460 to 1090	137.9 to 331.0	500 to 1200	850
Natural gas	96.6 to 179.31	350 to 650	110.3 to 215.2	400 to 780	590
Hard coal	193.1 to 262.1	700 to 950	206.9 to 344.8	750 to 1250	1000
Hard coal IGCC with CO_2 capture	*52.4* to *60.7*	*190* to *220*	*38.6* to *46.9*	*140* to *170*	*155*
Large scale wood chips combustion	–	–	21.0 to 23.0	76.0 to 83.3	79.6
Large scale wood chips gasification	–	–	6.0 to 8.0	21.6 to 29.0	25.3
Large scale biomass IGCC with CO_2 capture	*−139.4* to *−143.5*	*−505* to *−520*	*−35.9* to *−41.4*	*−130* to *−150*	*−140*
Large scale straw combustion	–	–	62.0 to 70.0	223.2 to 252.0	237.6
Biomass (wood chips) CHP large scale	–	–	6 to 10	21.6 to 36.0	28.8
Biomass (wood chips gasification) CHP small scale	–	–	3 to 6	10.8 to 21.6	16.2

Table 4
Long-term private costs of power generation technologies (2030–2050) (EUR/MWh).

Current			
Fuel or energy type	Costs (EUR/MWh)		Average private costs (EUR/MWh)
	Min	Max	
Nuclear	24	42	33
Oil	79	100	90
Natural gas	53	60	57
Hard coal	21	44	33
Hard coal IGCC with CO_2 capture	*40*	*43*	*42*
Large scale wood chips combustion	35	38	37
Large scale wood chips gasification	42	49	46
Large scale biomass IGCC with CO_2 capture	*57*	*60*	*59*
Large scale straw combustion	44	48	46
Biomass (wood chips) CHP large scale	37	60	49
Biomass (wood chips gasification) CHP small scale	37	60	49

5. Ranking of future electricity generation technologies based on carbon price developments

Seeking to compare electricity generation technologies based on carbon price developments several most reliable scenarios were selected: first best and second best scenarios. The average data for global region (the average over four regions: OECD, EEX, DevAsia, ROW) on carbon price were applied in analysis. The first best scenarios (FB-3p2 and FB-3p5) include specific targets: 3.2 W/m^2 and 3.5 W/m^2. The second best scenarios (SC) also include 3.5 W/m^2 and 3.2 W/m^2 targets and two options for GHG emission reduction commitments for world regions: (SC2) include GHG emission reduction commitments just for OECD–GHG emission reduction in 2050 by 90% from 2005 levels and (SC1) include different commitments for OECD (80% reduction in 2050 from 2005 level); energy exporting countries (50% reduction in 2050 from 2005 level); developing Asia countries (25% increase in 2050 from 2005 level) and for the rest of the world (55% increase in 2050 from 2005 level).

The ranking of 11 main future electricity generation technologies for 2020 and 2050 based on external costs of GHG emissions is the same as the same life cycle GHG emissions were applied for technologies assessment in all time frames. The most attractive technologies according external costs of GHG emissions in 2020 are: biomass IGCC with CO_2 capture, small scale biomass CHP (wood chips gasification), large scale wood chips gasification, large scale biomass CHP (wood chips combustion), nuclear, large scale wood chips combustion, hard coal IGCC with CO_2 capture. Less attractive technologies are: large scale straw combustion, natural gas, oil and hard coal. The ranking of electricity generation technologies based on external and private costs for the first best scenario in 2020 and 2050.

In Figs. 1 and 2 the range and average values of total (private and external costs of GHG emissions) costs of electricity generation technologies are presented in 2020 and 2050, respectively, according the more strict first best policy scenario FB-3p2.

As one see from Fig. 1 because of large uncertainties related with life cycle GHG emission and private costs of power generation technologies the ranking of electricity generation technologies is quite complicated however from Fig. 1 is obvious that the best electricity generation option in 2020 is nuclear following by large

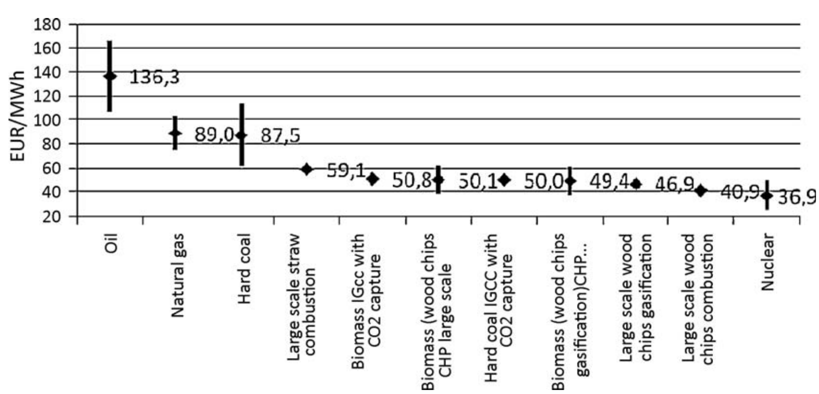


Fig. 1. The range of total (private and external costs of GHG emissions) costs of electricity generation technologies in 2020 according the more strict first best policy scenario FB-3p2.

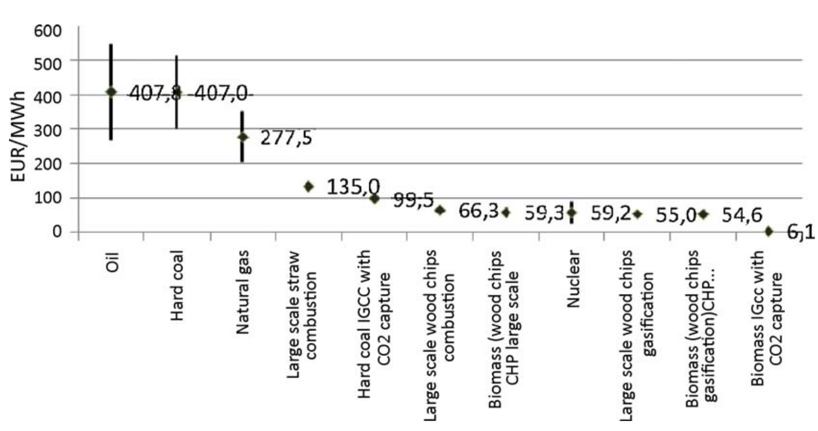


Fig. 2. The range of total (private and external costs of GHG emissions) costs of electricity generation technologies in 2050 according the more strict first best policy scenario FB-3p2.

scale wood chips combustion and other biomass technologies. Oil based technologies are the least attractive following natural gas and coal technologies. The most expensive biomass based technology in 2020 is large scale straw combustion technology. Hard coal with CO_2 capture technology is ranked in the same order like most biomass based technologies including biomass with CO_2 capture.

In 2050 the ranking of electricity generation technologies according the same scenario (Fig. 2) even taking into account big uncertianties and wide range of total costs for electricity generation technologies provides completeley different results. The most competetive technology in 2050 is biomass ICGG with CO_2 capture, following by other large scale biomass technologies and nuclear. Oil, hard coal and natural gas based technologies are the least competetive technologies in 2050. Hard coal with CO_2 capture is less attractive technology comparing with variety of biomass based technologies except large scale straw combustion.

Therefore the ranking of 11 future electricity generation technologies based on total costs in 2020 and 2050 is quite different. This is related with the fact that the high carbon prices in 2050 have significant impact on technologies ranking as external costs of GHG emissions overweigh private costs of electricity generation technologies. The most competitive technologies according total costs (private and external costs of GHG emissions) in 2020 are: nuclear, large scale wood chips combustion, large scale wood chips gasification, biomass (wood chips gasification) CHP small scale, hard coal IGCC with CO_2 capture, biomass (wood chips) CHP large scale and biomass IGCC with CO_2 capture. Total costs of these first ranked technologies are quite similar except nuclear. The less attractive technologies are: large scale straw combustion, hard coal, natural gas and oil. In 2050 the following ranking of the same electricity generation technologies based on total costs is provided: biomass IGCC with CO_2 capture, biomass (wood chips gasification) CHP small scale, large scale wood chips gasification, nuclear, biomass wood chips CHP large scale, large scale wood chips combustion, hard coal IGCC with CO_2 capture, large scale straw combustion, natural gas, hard coal and oil.

Seeking to compare the impact of private costs on electricity generation technologies ranking in different time frames in Figs. 3 and 4 the ranking of electricity generation technologies (world) in 2020 and 2050 accordingly is provided based on external costs of GHG emissions and total costs according the first best policy scenario FB-3p2.

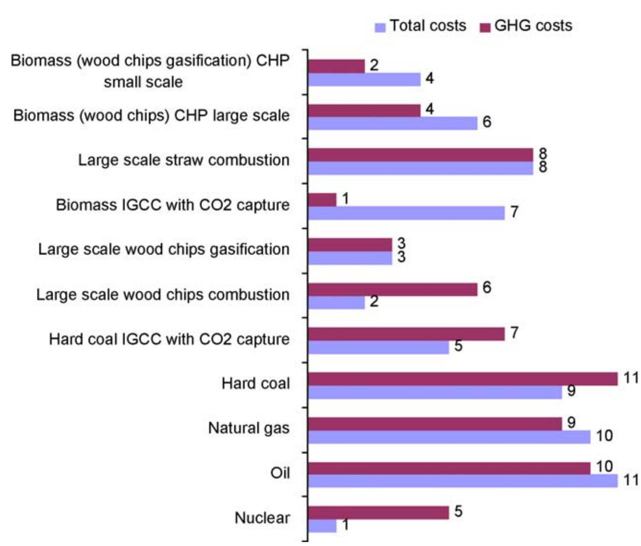


Fig. 3. Ranking of electricity generation technologies (world) in 2020 based on external costs of GHG emissions and total costs for the first best policy scenario FB-3p2.

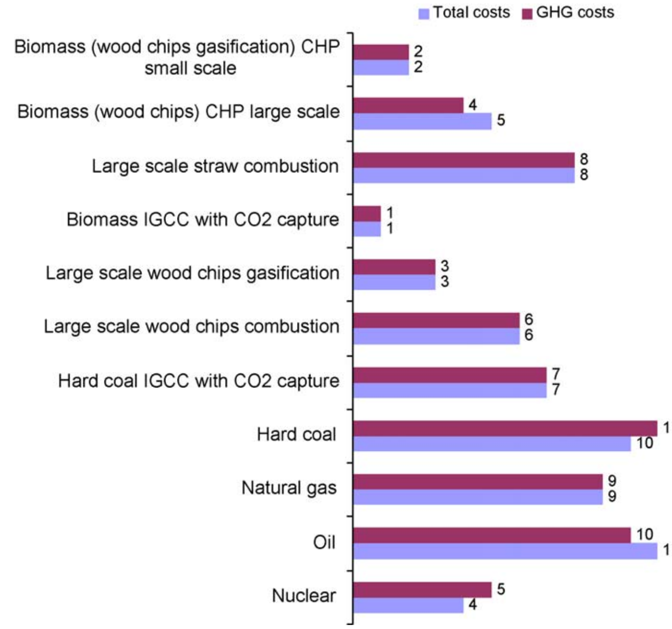


Fig. 4. Ranking of electricity generation technologies (world) in 2050 based on external costs of GHG emissions and total costs for the first best scenario FB-3p2.

As one can see from Fig. 3 the ranking of 11 future electricity generation technologies in 2020 according external costs of GHG emissions and total costs provides for quite different results as carbon price is not high enough in 2020 to overweight the impact of external costs of GHG emissions on technologies ranking. The following ranking of electricity generation technologies in 2020 based on total costs is achieved: nuclear, large scale wood chips combustion, large scale wood chips gasification, biomass (wood chips gasification) CHP small scale, hard coal IGCC with CO_2 capture, biomass (wood chips) CHP large scale and biomass IGCC with CO_2 capture, large scale straw combustion, hard coal, natural gas and oil. The ranking of electricity generation technologies according GHG external costs provides the following ranking: biomass IGCC with CO_2 capture, biomass (wood chips gasification) CHP small scale, large scale wood chips gasification, biomass wood chips large scale CHP, nuclear, large scale wood chips combustion, hard coal IGCC with CO_2 capture, large scale straw combustion, natural gas, oil and hard coal.

As one see from Fig. 4 the ranking of electricity generation technologies according external costs of GHG emissions and total costs in 2050 is quite similar for the presented scenario FB-3p2 just ranking order of oil and hard coal technologies has changed then private costs were added to external costs of GHG emissions. External GHG emission costs as it was already mentioned are the highest for hard coal technologies, followed by oil and natural gas technologies however taking into account private costs hard coal technologies is cheaper than oil. The significant impact of external costs of GHG emissions in 2050 because of the high carbon price is crucial for technologies ranking in 2050.

The ranking of electricity generation technologies according external costs of GHG emissions and total costs (private and external) costs is similar for less strict first best policy scenario where 3.5 W/m^2 target is imposed instead of 3.2 W/m^2. For all policy scenarios electricity generation technologies ranking in 2020 and 2050 based on external GHG costs provides the same results because of the same life cycle GHG emission data of electricity generation technologies.

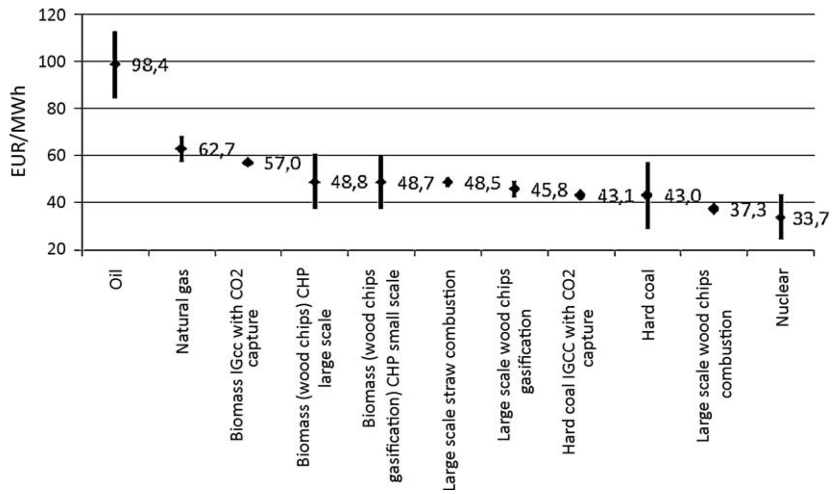


Fig. 5. The range and average total costs of electricity generation technologies (world) in 2020 according the second best scenario SC1-3p2.

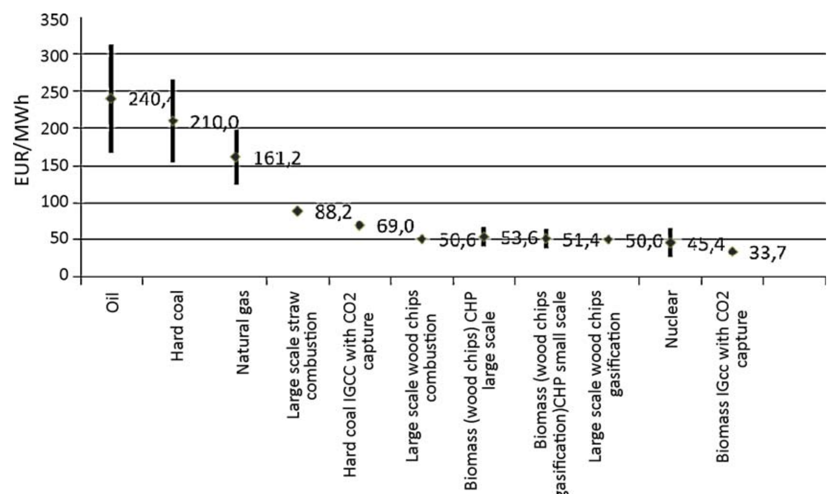


Fig. 6. The range and average total costs of electricity generation technologies (world) in 2050 according the second best scenario SC1-3p2.

In Figs. 5 and 6 the range of total costs and average costs of electricity generation technologies in 2020 and 2050, respectively, according the second best policy scenario SC1-3p2 is presented.

As one can see from Fig. 5 the most competetive technology according the second best scenario SC1-3p2 in 2020 like in the case the first best policy scenario is nuclear followed by large scale wood chips combustion technologies however the hard coal based technologies are ranked in the same order. This is because of low carbon price in 2020 according this scenario as private costs of hard coal based technologies overweight impacts of external GHG emission costs. Biomass IGCC with CO_2 capture technologies because of quite high private costs are less competetive in 2020 according this scenario. The most expensive technologies like in the case of first best scenario are oil, hard coal and natural gas based technologies.

The most competitive electricity generation technology in 2050 according the second best policy scenario (Fig. 6) like in the case of the first best policy scenario is biomass IGCC with CO_2 capture however the nuclear is ranked as second best technology. The lower carbon price of second best scenario has impact on the competitiveness of electricity generation technologies as external costs of GHG emissions according this scenario do not overweight private costs of some technologies like in the case of first best scenario therefore provides for different ranking in first bets and second best policy scenarios.

Though quite different ranking of electricity generation technologies is obtained for various scenarios and time frame the results obtained in technologies ranking based on external GHG emission costs and total costs are similar just for FB-3p2 scenario in 2050 because of very high carbon price (375 EUR/tCO_2 eq.). External costs of GHG emissions in FB-3p2 scenario in 2050 overweight impact on private costs in technologies ranking.

For all other policy scenarios electricity generation technologies ranking based on total costs and GHG emission costs provides for different results in technologies ranking. The most expensive technology in terms of total costs for all main policy scenarios in 2020 and 2050 is oil. The most competitive technology for all scenarios in 2020 is nuclear and in 2050—biomass IGCC with CO_2 capture. Biomass IGCC with CO_2 capture is the most competitive in technologies assessment based on total GHG emission costs. The hard coal, oil and natural gas technologies are among the most expensive for all policy scenarios and all time frames. In 2050 because of the high carbon prices in all scenarios natural gas technologies are more competitive and in 2020 coal technologies are more competitive than natural gas technologies as private costs overweight external costs of GHG emissions in comparative assessment of technologies. In the ranking of technologies based on external costs of GHG emissions the coal technologies are the last attractive one. The ranking of biomass technologies based on total costs is different for specific scenarios and time frame and

depends on carbon price obtained by specific scenarios. Very high carbon prices make more competitive technologies having low life cycle GHG emission such as biomass IGCC with CO_2 capture, biomass wood chips gasification and biomass CHPs technologies though these technologies in terms of private costs are more expensive than other biomass technologies external costs of GHG emissions in high carbon price scenarios overweight the private costs in technologies ranking. Hard coal with CO_2 capture technologies is ranked in the middle and in 2050 have similar total costs as large scale straw combustion technologies.

6. Conclusions

The long-term assessment of new energy technologies was performed in the paper for various long-run policy scenarios taking into account two main criteria: private costs (ALLGC) and external GHG emission costs. Such policy oriented energy technologies assessment based on carbon price and private costs of technologies can provide information on the most attractive future energy technologies taking into account climate change mitigation targets and GHG emission reduction commitments for world regions.

The ranking of energy technologies based on costs (private, external and total) points to a general problem in having costs as the main parameter for comparison of different technologies since these energy technologies do not compete on the same markets. Energy technologies show a large span in costs and efficiencies and different processes yield different installed capacities therefore it is problematic to compare such processes if comparison is only made on cost basis since the different processes are suitable for different markets however comparison of different energy technologies based on total costs and carbon price enables to develop some important policy recommendations even taking into account high uncertainties in private and external costs.

Analysis of life cycle GHG emissions and private costs of the main future electricity generation technologies performed in the paper indicated that biomass technologies except large scale straw combustion technologies followed by nuclear have the lowest life cycle GHG emission. The cheapest future electricity generation technologies in terms of private costs in long-term perspective are: nuclear and hard coal technologies followed by large scale biomass combustion and biomass CHPs. The most expensive technologies in terms of private costs are: oil and natural gas technologies. As the electricity generation technologies having the lowest life cycle GHG emissions are not the most expensive but not the cheapest one in terms of private costs the ranking of technologies in terms of competitiveness highly depends on the carbon price implied by various policy scenarios integrating specific GHG emission reduction commitments taken by countries and set climate change mitigation targets.

The assessment of the main selected power technologies based on external costs of GHG emissions and total costs was performed in 2020 and 2050 for the first best (FB-3p2) and second best scenarios (SC1-3p2; SC2-3p2). Scenarios with more strict targets (3.2 M/m^2) were selected for technologies assessment.

Eleven main future electricity generation technologies were selected: nuclear, oil, natural gas, hard coal including hard coal technologies with CO_2 capture and various biomass technologies (wood chips combustion, gasification, CHP, straw combustion, biomass IGCC with CO_2 capture). For all policy scenarios electricity generation technologies ranking in 2020 and 2050 based on external GHG costs provides the same results as the same data on life cycle GHG emissions were applied for technologies ranking. The most competetive technology according all policy scenarios based on external GHG costs in 2020 and 2050 is biomass IGCC with CO_2 capture biomass followed by other biomass technologies. Nuclear is ranked in the middle.

Though quite different ranking of electricity generation technologies is obtained for various scenarios and time frames the results obtained in technologies ranking based on external GHG emission costs and total costs are similar just for FB-3p2 scenario in 2050 because of very high carbon price (375 EUR/tCO_2 eq.). External costs of GHG emissions in FB-3p2 scenario in 2050 overweight impact on private costs in technologies ranking. For all other policy scenarios electricity generation technologies ranking based on total costs and GHG emission costs provides for different results in technologies ranking. The most expensive technology in terms of total costs for all main policy scenarios in 2020 and 2050 is oil. The most competitive technology for all scenarios in 2020 is nuclear followed by large scale wood chips combustion technologies and in 2050 biomass IGCC with CO_2 capture followed by biomass wood chips gasification CHP small scale having the lowest life cycle GHG emissions among analysed technologies except biomass with CO_2 capture. This technology is the most competitive in technologies assessment based on total GHG emission costs as well. The hard coal and natural gas technologies are among the most expensive for all policy scenarios.

In 2050 because of the high carbon prices in all policy scenarios natural gas technologies are more competitive than coal and in 2020 coal technologies are more competitive than natural gas technologies as private costs overweight external costs of GHG emissions in comparative assessment of technologies. In the ranking of technologies based on external costs of GHG emissions the coal technologies are the least attractive one. The ranking of biomass technologies based on total costs is different for specific scenarios and time frames and depends on carbon price obtained by specific scenarios. Very high carbon prices make more competitive technologies having low life cycle GHG emission such as biomass IGCC with CO_2 capture and biomass wood chips gasification technologies though these technologies in terms of private costs are more expensive than other biomass technologies nevertheless the external costs of GHG emissions in high carbon price scenarios overweight the private costs in technologies ranking.

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